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Classroom indoor air quality and noise level assessment of different educational institutions in a university area in Bangladesh

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ABSTRACT

Introduction: The classroom environment is crucial for fostering effective learning and safeguarding teacher-student health. This study assessed the Indoor Air Quality (IAQ) and noise levels in classrooms across three institutions: a university, a secondary and higher secondary school (called a school and college), and a primary school.

Materials and methods: Various IAQ parameters such as Particulate Matters ($PM_{2.5}$ and PM_{10}), Carbon monoxide (CO), Carbon dioxide (CO_2), Total Volatile Organic Compound (TVOC), and temperature, Relative Humidity (RH), light, and noise levels were measured using calibrated instruments from February to March 2024.

Results: The air pollutants and noise levels varied among the institutions. The mean values of $PM_{2.5}$ (76.6 µg/m^3) and PM_{10} (116.7 µg/m^3) were highest in the primary school, while CO (0.82 ppm), light (92.9 lux), temperature (27.6 °C), and noise levels (77.6 dB) peaked in the school and college. University classrooms showed the maximum concentrations of CO_2 (804.9 ppm), TVOC (32.9 ppb), and RH (58.6%). In all institutions, $PM_{2.5}$, PM_{10}, and noise levels exceeded WHO-recommended limits, whereas CO, CO_2, RH, and temperature remained within their respective standards. Light levels were below Occupational Safety and Health Administration (OSHA) guidelines. Correlation analysis showed significant positive correlations between $PM_{2.5}$, PM_{10}, and CO. Hazard Quotient (HQ) values for $PM_{2.5}$ and PM_{10} exceeded 1.0, indicating potential health risks. Variations in pollutants and noise levels among institutions may be due to classroom facilities, student density, ventilation systems, and student activities.

Conclusion: Long-term exposure to IAQ pollutants and noise levels could impair cognitive function, respiratory health, and overall well-being of the students and educators. Implementing proper ventilation (e.g., HEPA filters) systems, soundproofing acoustic panels, and continuous IAQ monitoring is recommended for a safer classroom environment.

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Introduction

Ensuring a high-quality classroom environment in educational institutions is vital for fostering effective learning and safeguarding teacher-student health [1]. Among the various factors contributing to an optimal classroom environment, Indoor Air Quality (IAQ) and noise levels are particularly influential. IAQ refers to the purity of the air within school buildings, encompassing the presence of pollutants and the adequacy of ventilation [2, 3]. Noise levels, on the other hand, refer to the ambient sound within classrooms, which can significantly affect concentration and learning outcomes [4, 5]. Therefore, the assessment of the classroom IAQ and noise levels is crucial for students and teachers who spend significant time on these premises.

The impact of IAQ in educational settings is gaining attention due to its direct effects on the health and cognitive functions of students [6]. Poor IAQ can lead to a myriad of health issues, such as respiratory infections, asthma, and allergies, all of which can hinder effective learning [7, 8]. Additionally, high levels of Carbon dioxide (CO_2), Volatile Organic Compounds (VOCs), and Particulate Matter (PM) can cause headaches, dizziness, and fatigue, further impairing cognitive performance [9, 10]. In primary schools, where young children are still developing their respiratory systems, the implications of poor IAQ are particularly severe [11]. Students in high schools, colleges, and universities face increased academic pressures, and suboptimal air quality can exacerbate stress and reduce academic performance [12].

Noise pollution also negatively affects students' ability to concentrate and learn. High noise levels can cause distractions, increase stress, and reduce cognitive function, which makes it difficult to engage with the contents and retain information [13]. Primary school students are particularly susceptible to noise disruptions due to their progressing attention spans and learning capacities [14]. In high schools, the transition to more complex and demanding coursework requires a quieter environment to facilitate deep concentration and effective learning [15]. Universities, with their diverse learning activities and environments, face unique challenges in maintaining appropriate noise levels [16].

Previous studies have explored IAQ or noise levels in educational classrooms across various countries. For instance, a study at the University of Limpopo, South Africa, found that air pollutant levels varied across departments, posing health risks [17]. Research in Beijing, China, indicated that particulate and gaseous air pollutants in primary schools adversely affected children's respiratory health [18]. Similarly, studies in Thailand [19], Malaysia [20], Saudi Arabia [21], Kuwait [22], and Morocco [23] highlighted the health issues associated with poor IAQ and high noise levels in educational settings. In Bangladesh, several studies [12, 24, 25] noted that air and noise pollution in schools and universities threatens students' health and academic success; however, these studies typically focus on IAQ or noise levels in isolation within specific educational contexts.

The current study aims to address this gap by combining the assessment of IAQ and noise levels across three types of institutions—primary school, school and college, and university—in a university area of Chattogram, Bangladesh. The study assessed various IAQ and noise parameters in the selected classrooms of these three types of institutions. IAQ parameters such as Carbon dioxide (CO_2), Carbon monoxide (CO), Total Volatile Organic Compound (TVOC), particulate matter ($PM_{2.5}$ and PM_{10}), temperature, light, and humidity were monitored. The study also evaluated the correlation among the measured parameters. This study is particularly crucial in developing countries like Bangladesh for understanding the current state of IAQ and noise levels in classrooms and suggesting improvements to enhance the well-being and academic performance of students and teachers.

Materials and methods

Study locations

The study was conducted on the campus of Chittagong University of Engineering & Technology (CUET), a prominent university situated in the Chattogram district of Bangladesh, at coordinates of 22.4619° N and 91.9711° E. The university campus spans 171 acres and is located 25 km from the center of Chattogram City. Similar to other regions in Bangladesh, the campus experiences four distinct climate seasons: Winter (December-February), Summer (March-May), Monsoon (June-September), and Post-Monsoon (October-November), each characterized by varying temperatures, precipitation, and humidity levels.

Within the university area, there is one primary school, one secondary and higher secondary school (called school & college), and various academic, administrative, and residential facilities. For this study, the primary school, the school & college, and one academic building (Building 1) were selected to assess the IAQ and noise level of their classrooms. The specific locations of the study area and data collection points are illustrated in Fig. 1.

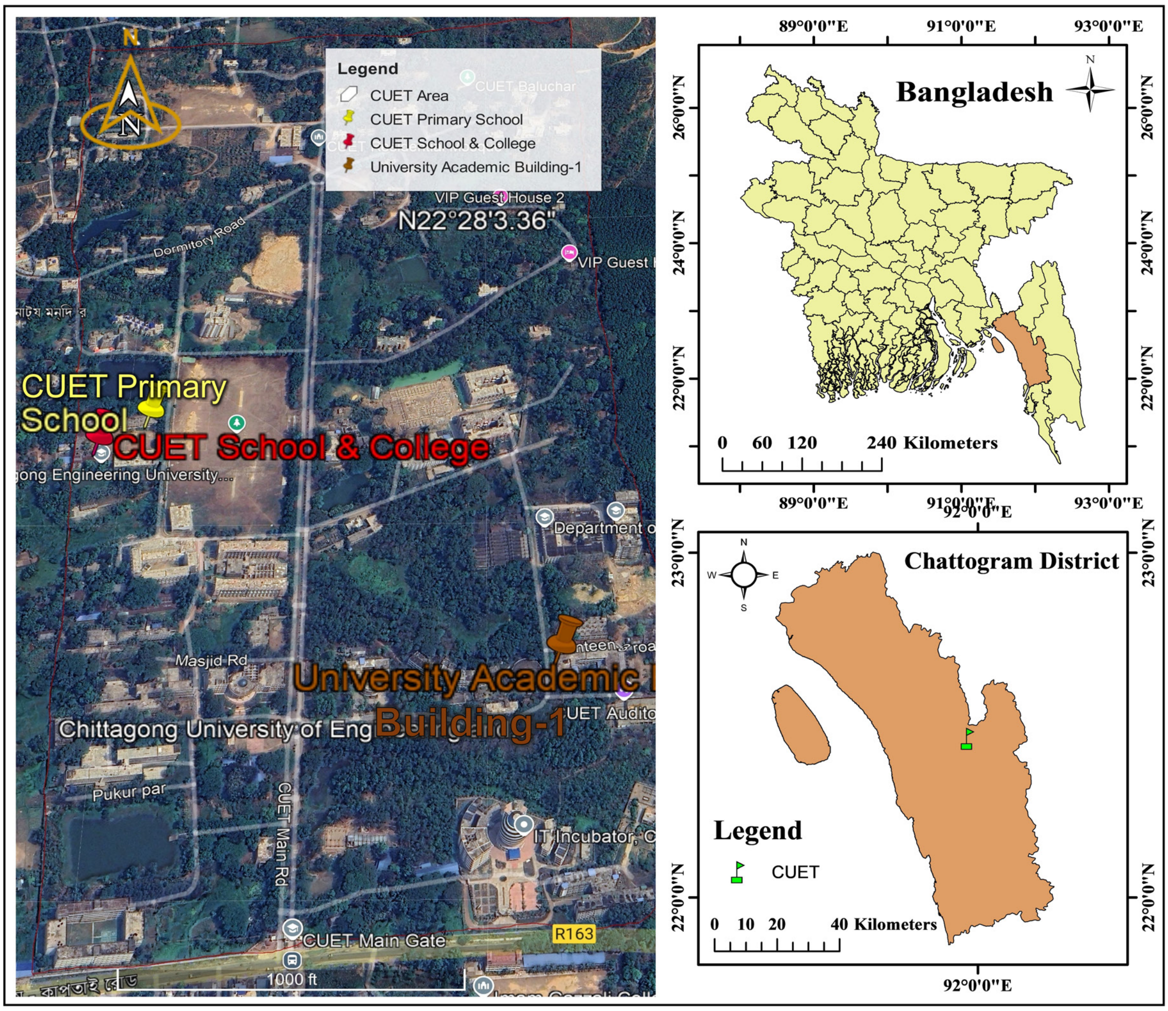

Fig. 1. Location of study area and data collection points

Data collection

Different parameters affecting indoor air quality, such as particulate matter ($PM_{2.5}$ and PM_{10}), gaseous air pollutants (CO, CO_2, and TVOC), noise levels, and meteorological conditions (temperature, humidity, and light), were measured. Indoor parameter measurements were conducted during class times (spanning 45–60 minutes) at 5-minute intervals from February to March 2024.

A total of nine classrooms were selected for measurements, comprising three classrooms (classes 1, 3, and 5) from the primary school, four classrooms (classes 7, 8, 10, and 11) from the school & college, and two classrooms (years 2nd and 3rd) from the university. Measurements were carried out using calibrated instruments following the manufacturer's guidelines and the IAQ handbook [26]. The technical specifications of the measuring instruments, along with standard parameter values, are summarized in Table 1. The measuring instruments were positioned 76.2 cm above the classroom floor during data collection.

Table 1. Technical specifications of the measuring instruments and standard limits of different parameters

Parameter	Measuring instruments	Analytical principle	Range	Accuracy	Reference Limits
$PM_{2.5}$ (µg/m^3)	Temtop Air Quality Monitor (M2000C)	Laser sensor	0-999 µg/m^3	±10 µg/m^3; ±10%	15 µg/m^3 (24 h [27]
PM_{10} (µg/m^3)	Temtop Air Quality Monitor (M2000C)	Laser sensor	0-999 µg/m^3	±15 µg/m^3; ±15%	45 µg/m^3 (24 h [27]
CO (ppm)	Graywolf AdvancedSense Pro-Environmental Test Meter	Electrochemical	0-500 ppm	±2 ppm <50ppm, ±3 rdg >50ppm	35 ppm (1 h)/ 10 ppm (8 h)/ 4ppm (24 h) [27, 28]
CO_2 (ppm)	Graywolf AdvancedSense Pro-Environmental Test Meter	Non-Dispersion Infrared Detector	0-10,000 ppm	±3% rdg ±50ppm	1000 ppm (8 h) [29]
TVOC (ppb)	Graywolf AdvancedSense Pro-Environmental Test Meter	Photoionization detector	5-20,000 ppb	Resolution 1ppb, L.O.D <5ppb	500 µg/m^3 [30]
Temp (°C)	Graywolf AdvancedSense Pro-Environmental Test Meter	Platinum100	-25°C to +70°C	±0.3°C	19.4-27.8 °C [31]
RH (%)	Graywolf AdvancedSense Pro-Environmental Test Meter	Capacitive	0-100 %RH	±2% RH for <80% RH (±3% RH for >80% RH	30 %– 60 % [31]
Light	Victor Digital Lux Meter (VC-1010A)	Photodiode sensor	0.1~50000 Lux	±4% rdg+10 Lux	300 Lux [32]
Noise Level	Casella Digital Sound Level Meter (Cel-246)	Digital signal processing/ Microphone	30-100 dB	±1dB Calibration range	35 dB [33]

Data analysis

The data analysis encompassed several techniques, including descriptive analysis, correlation analysis, Principal Component Analysis (PCA), air-related health risk assessment, and examination of various noise parameters. These analyses were conducted for all measured parameters across the classrooms of the three institutions. Descriptive statistics, such as mean, median, Standard Deviation (SD), maximum, and range, were computed using Statistical Package for the Social Sciences (SPSS v22). Pearson parametric correlation analysis was performed and visualized in correlation plots using OriginPro 2021. The correlation coefficient at 95% ($\rho<0.05$) and 99% ($\rho<0.01$) confidence intervals were considered significant. The coefficient value ranges from -1 to +1, where values closer to -1 or +1 indicate strong negative or positive associations between parameters, respectively, while values close to 0 indicate no association [34].

PCA was conducted to identify factor loadings associated with each Principal Component (PC), and Hierarchical Clustering Diagrams (HDA) were used to observe parameter clusters and their association with other clusters. PCA loadings close to +1 or -1 indicate a strong influence of the PC on the parameters, while values close to 0 suggest a weak influence [35]. Both PCA and HDA were performed using OriginPro software. In addition, air-related health risk assessment and analysis of different noise parameters are discussed in subsequent subsections.

Air-related health risk assessment

Health risk assessment evaluates the potential impact on individuals exposed to specific pollutants over a defined period. In this study, the exposure of students and teachers in classrooms to air pollutants was assessed using the USEPA health risk assessment method. Non-carcinogenic risks associated with five air pollutants ($PM_{2.5}$, PM_{10}, CO, CO_2, and TVOC) in the indoor classrooms of the three buildings were calculated using the Hazard Quotient (HQ).

The HQ is a metric that compares the potential exposure level to a pollutant against a reference concentration at which no adverse effects are expected. It is computed to estimate the probability that exposure to non-carcinogenic pollutants may harm health. An HQ greater than 1 indicates a likelihood of non-cancer risk, whereas an HQ less than or equal to 1 indicates no health risk [17]. The following Equation is used to calculate the HQ [36].

$$HQ = \frac{C*ED*EF}{RfC*AT} \quad (1)$$

Where C represents the concentration of air pollutants (units corresponding to the parameters), ED is the exposure duration (years), EF is the exposure frequency (number of classroom days in a year), RfC is the reference concentration of the pollutants (units matching C), and AT is the exposure time (days), calculated as ED multiplied by 365. The ED for teachers was considered to be 30 years, while for students, it varied based on their academic years (5, 7, or 4 years). EF values differed for teachers and students (see Table 5), determined according to the Bangladesh academic calendar and consultations with teachers and students of the respective institutions.

The total non-carcinogenic risk is represented by the sum of individual air pollutant HQ values, referred to as the Hazard Index (HI), defined as follows [37]:

$$HI = \sum_i HQ_i \quad (2)$$

In Eq. 2, HQ corresponds to the five air quality parameters mentioned above. If HI is greater than 1, there is a possible significant non-cancer risk, while if HI is equal to or less than 1, there is no significant non-cancer risk for adverse health [38].

Different noise parameters measurement

Noise level is a measure of the intensity of sound/noise, expressed on a logarithmic scale known as decibels (dB). Monitoring noise levels is crucial for identifying potential human health issues and giving effective solutions. Due to the temporal fluctuations in noise levels, a representative statistical measure known as the equivalent continuous noise level (L_{eq}) is utilized. L_{eq} captures temporal fluctuations into a single value that represents the average sound energy calculated using the Equation:

$$L_{eq} = 10* \log_{10}[\frac{1}{N}\sum_i 10^{(\frac{L_i}{10})}] \quad (3)$$

Where L_i is the average noise level during interval i.

Another parameter, Noise Pollution Level (L_{np}), provides a more comprehensive indicator by considering varying noise levels. It serves as a measure of the potential psychological impacts of noise pollution on human health [39]. L_{np} can be calculated as follows:

$$L_{np} = L_{50} + \frac{(L_{10}-L_{90})^2}{60} + (L_{10} - L_{90}) \quad (4)$$

Where L_{10}, L_{50}, and L_{90} denote the noise levels exceeded for 10%, 50%, and 90% of the time, respectively, within a given timeframe (Fig. 2).

Furthermore, Noise Climate (NC) characterizes ambient noise conditions, reflecting the fluctuating range of sound levels in a specific environment over a specified period. It is expressed as:

$$NC = L_{10} - L_{90} \quad (5)$$

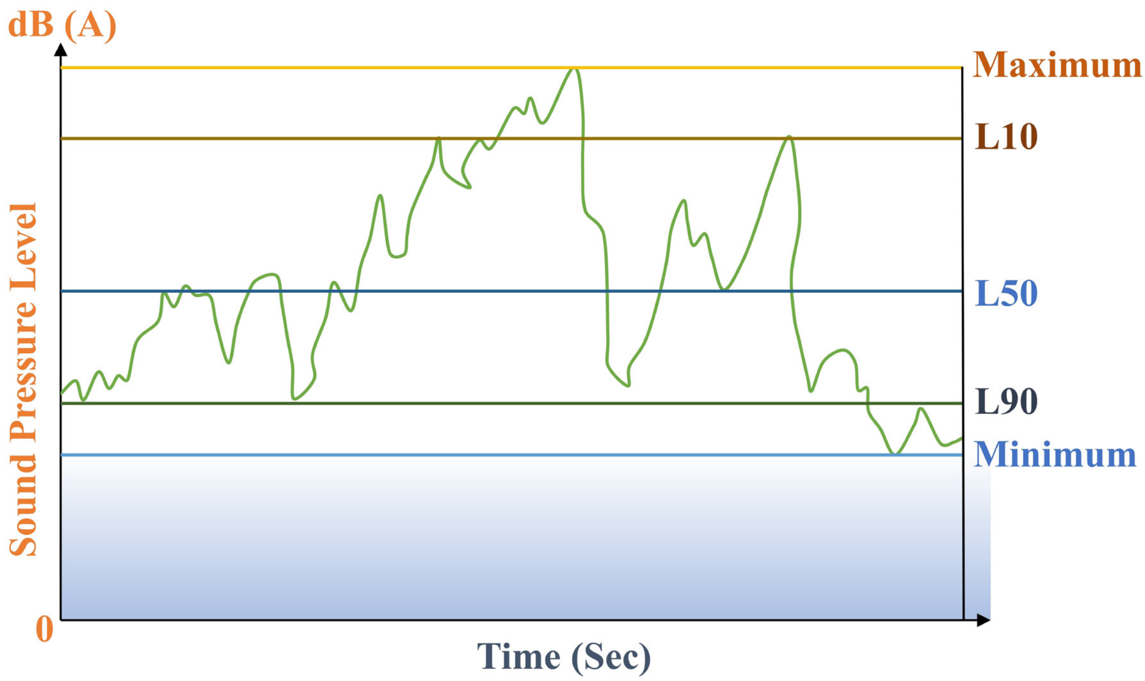

Fig. 2. Representative different noise parameters (figure updated from the reference [40])

Results and discussion

Measured parameters status

Different measured parameters vary across the institutions, as depicted in Fig. 3. Table 2 provides descriptive statistics for these parameters. Mean values of $PM_{2.5}$ and PM_{10} were highest in the primary school classrooms, while CO, light, temperature, and noise levels were highest in the school and college classrooms. Conversely, CO_2, TVOC, and RH were highest in the university classrooms. According to the US EPA breakpoints presented in Table 3, the mean values of $PM_{2.5}$ (64.29–76.58 µg/m^3) fell within the unhealthy category, while PM_{10} (96.89–116.72 µg/m^3) were classified as moderate. CO levels (0.64-0.72 ppm) were rated good, and CO_2 concentrations (608.36–804.89 ppm) were deemed good to moderate. Additionally, the maximum values of $PM_{2.5}$ (96–125 µg/m^3) and CO (1.0–1.2 ppm) fell within the same categories as the mean values, except for PM_{10} and CO_2. Both maximum PM_{10} values (150–190 µg/m^3) and CO_2 concentrations (984–1311 ppm) were categorized as moderate to unhealthy for sensitive groups. It was also observed that PM ($PM_{2.5}$ and PM_{10}) and TVOC levels (particularly in university classrooms) exceeded their respective WHO or RESET standard limits (see Table 1). In contrast, CO and CO_2 levels remained within acceptable ranges set by WHO and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), respectively. Among other important parameters, light levels were significantly lower than the OSHA standards, noise levels exceeded the WHO guidelines, and relative humidity and temperature fell within the ASHRAE recommendations.

In Figs. 3a and 3b, $PM_{2.5}$ and PM_{10} showed higher values (76.58 and 116.72 µg/m^3) for primary school classrooms compared to high school & college, and university. The major causes for these findings were children's activities, chalk use for blackboard writing, inefficient ventilation systems, and limited classroom cleaning practices. A study in Korea found mean PM_{10} levels of 101.25 to 115.25 µg/m^3, attributing the higher values to higher occupancy and student activities (walking/playing), which cause particulate matter resuspension in classrooms [41]. A study found that even a small number of children can increase PM concentrations in classrooms [42]. Another study indicated that schools using chalkboards have higher $PM_{2.5}$ levels compared to those using whiteboards [43]. Likewise, in Figs. 3d and 3e, the high CO_2 (804.9 ppm) and TVOC (328.9 ppb) levels in university classrooms were due to higher student density, insufficient outdoor air exchange, and nearby laboratory activities. Previous studies have shown that inadequate ventilation results in elevated CO_2 levels in classrooms [3, 44]. Insufficient ventilation, combined with cleaning activities, also contributes to high TVOC levels [45].

Figs. 3g and 3h show closely varied temperatures (27.26 and 27.56 °C) in the university and the school & college, but high RH (58.61%) in the university classrooms. High RH and temperatures in university classrooms were due to the same causes mentioned for CO_2 and TVOC. A study in Serbian school buildings found that RH and temperature are positively correlated with CO_2 [46]. Another indoor parameter, light, was found to be lower (46.7 Lux) in primary schools, as shown in Fig. 3f. The lower light intensity in primary schools was due to old and insufficient light fixtures and a lack of natural light systems (windows). Light intensity below the standard level of 300 Lux is not recommended for students' academic performance, as indicated in previous studies [47, 48]. A study in the UK showed that 80% of classrooms are illuminated with 100 Hz fluorescent lights, which can cause headaches and reduce visual performance [47].

Comparatively high noise levels (>35 dB) were found in the school and college (77.58 dB) and the primary school (77.21 dB) (Fig. 3i), indicating poor classroom conditions for teaching and learning. A study in Nigeria mentioned that daytime noise levels ranged from 68.3–84.7 dBA in secondary schools, disturbing students in the classrooms [49]. The high noise level in the school and college was due to students gossiping and sound systems used during classes. Similar results were observed in previous studies [50–52], which noted that excessive noise in classrooms can disrupt the learning process and negatively impact the physical and mental health of teachers and students.

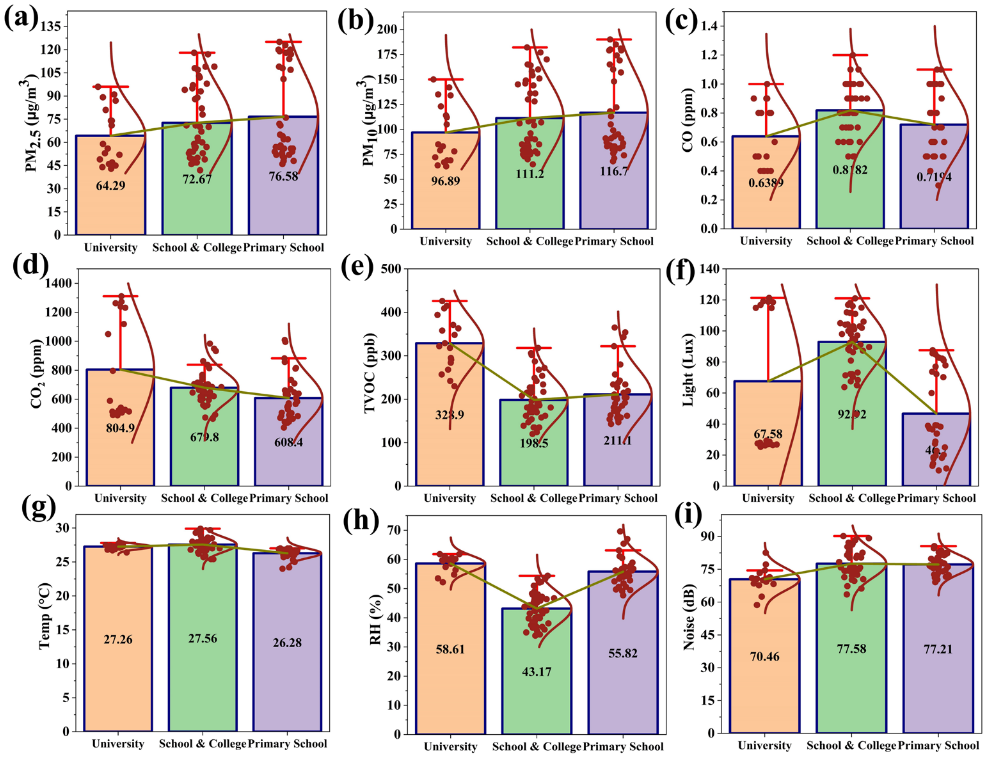

Fig. 3. Variation of measuring parameters in different types of institutions

Table 2. Descriptive statistics of different parameters in different institutions

Parameters	University					School and College					Primary School				
	Mean	SE	Median	Max	Range	Mean	SE	Median	Max	Range	Mean	SE	Median	Max	Range
$PM_{2.5}$ (μg/m^3)	64.29	4.37	57.5	96	53	72.67	3.52	65	118	76	76.58	4.77	62	125	79
PM_{10} (μg/m^3)	96.89	7.06	84	150	87	111.23	5.42	100	182	117	116.72	7.00	94	190	122
CO (ppm)	0.64	0.05	0.55	1	0.6	0.82	0.03	0.8	1.2	0.7	0.72	0.04	0.7	1.1	0.8
CO_2 (ppm)	804.89	81.47	565.5	1311	822	679.84	16.86	669	984	519	608.36	26.26	569.5	1009	605
TVOC (ppb)	328.89	14.31	325.5	426	196	198.48	7.60	187.5	318	198	211.14	9.77	202	365	222
Light (Lux)	67.58	10.97	28.95	121.3	96	92.92	2.60	96	121	74.6	46.70	4.55	35.05	87.6	77.5
Temp (°C)	27.26	0.09	27.3	27.8	1.4	27.56	0.17	27.55	29.9	4.5	26.28	0.12	26.45	27	3
RH (%)	58.61	0.64	59.55	61.8	9.6	43.17	0.85	42.45	54.4	20.5	55.82	0.82	55.7	69.6	21.9
Noise level (dB)	70.46	1.20	70.6	82.6	23.9	77.58	0.99	75.75	90.2	26.7	77.21	0.72	76.7	85.6	16.47

Table 3. Values of breakpoints and AQI index [53]

Parameters	Good (Green)	Moderate (Yellow)	Unhealthy for sensitive groups (Orange)	Unhealthy (Red)	Very Unhealthy (Purple)	Hazardous (Maroon)
AQI Index	0 - 50	51- 100	101 - 150	151 - 200	201 - 300	≥ 301
$PM_{2.5}$ (µg/m^3)	0 – 12.0	12.1 – 35.4	35.5 – 55.4	55.5 – 150.4	150.5 – 250.4	≥ 250.5
PM_{10} (µg/m^3)	0 – 54	55 – 154	155 – 254	255 – 354	355 – 424	≥ 425
CO (ppm)	0 - 4.4	4.5 – 9.4	9.5 – 12.4	12.5 – 15.4	15.5 – 30.4	≥ 30.5
CO_2 (ppm)	0 - 700	701 - 1000	1001 - 1500	1501 - 2500	2501 - 5000	≥ 5001

Correlation analysis

Each parameter has a positive or negative relationship with other parameters. Fig. 4 represents Pearson's correlation (at 99% and 95% confidence intervals) among the measured parameters for the three institutions. At the university, $PM_{2.5}$, PM_{10}, CO, CO_2, and light were significantly strongly correlated (p=0.80–1.0) at the 99% confidence interval. This strong correlation implies that these contaminants may originate from similar sources, such as indoor activities or nearby traffic emissions. Conversely, RH showed a negative correlation with all parameters, suggesting that increased humidity may result in lower concentrations of particulate matter and gases, thereby influencing indoor air quality. In the school and college, $PM_{2.5}$, PM_{10}, CO, and RH were significantly positively correlated (p= .44–1.00) at the 99% confidence interval (α=1%). In the primary school, $PM_{2.5}$, PM_{10}, CO, CO_2, light, and noise were significantly positively correlated (p=0.30–1.00) at 99% and 95% confidence intervals. Notably, no significant correlation was found between TVOC and noise in the university, nor between CO_2, light, and noise in the school and college relative to other parameters.

In all cases, $PM_{2.5}$, PM_{10}, and CO were significantly correlated with each other, consistent with a study conducted in Malaysia [54]. A negative association between temperature and relative humidity was observed in all cases, as they have an inverse relationship. Specifically, $PM_{2.5}$ and temperature were negatively correlated in both school & college and primary school settings, as supported by the previous study [55]. This negative correlation between temperature and $PM_{2.5}$ may be attributed to lower air circulation in colder climates, which can lead to higher concentrations of particulate matter. In all cases, TVOC showed weak or negative relationships with meteorological parameters, indicating that indoor TVOC is slightly influenced by these factors. Significant positive correlations were observed between CO_2 and TVOC in the primary school, CO_2 and $PM_{2.5}$ in the university, and TVOC and CO in the school and college, corroborating earlier findings [56]. These correlations provide valuable insights into the sources of pollution and can guide the implementation of appropriate measures to lower their concentrations.

PCA, a statistical method, is used to simplify large datasets by identifying similarities among them and clustering the data by transforming the original variables into Principal Components (PCs). PCs capture most of the variance in a dataset while maintaining its essential patterns and trends [35]. In this study, three PCs (PC1, PC2, and PC3) were selected based on their eigenvalues (>1). Table 4 summarizes the PCs and their loadings corresponding to the parameters. PC1 contributes to maximum variances of 62.29%, 50.57%, and 43.19% for the datasets of the university, primary school, and school & college, respectively. A high PC1 for the university indicates that the maximum variance (more than half) is explained by this PC. Among the 81 PC loadings, all parameters were found below an absolute value of 0.5 (except for nine loadings), indicating that most parameters have weak influences on the three PCs. Parameters with similar PC loading values indicate clusters, which are visualized in the HCA diagram (dendrogram) shown in Fig. 5.

In HCA with agglomerative clustering, variables with proximity are merged to form clusters, which are then connected to other clusters, continuing until all clusters are connected [57]. For the university parameters, light, CO_2, and CO form a cluster that is connected with another cluster formed by $PM_{2.5}$ and PM_{10}. Similarly, in the school & college datasets, TVOC and RH form clusters that connect with CO, and then with clusters of $PM_{2.5}$ and PM_{10}. In the primary school dataset, $PM_{2.5}$ and PM_{10} form clusters connected with CO, followed by light, and so on. The HCA analysis demonstrated that parameters with the smallest similarity (or largest distance) were connected last, supporting the findings from the previous correlation and PCA analyses shown in Fig. 4 and Table 4.

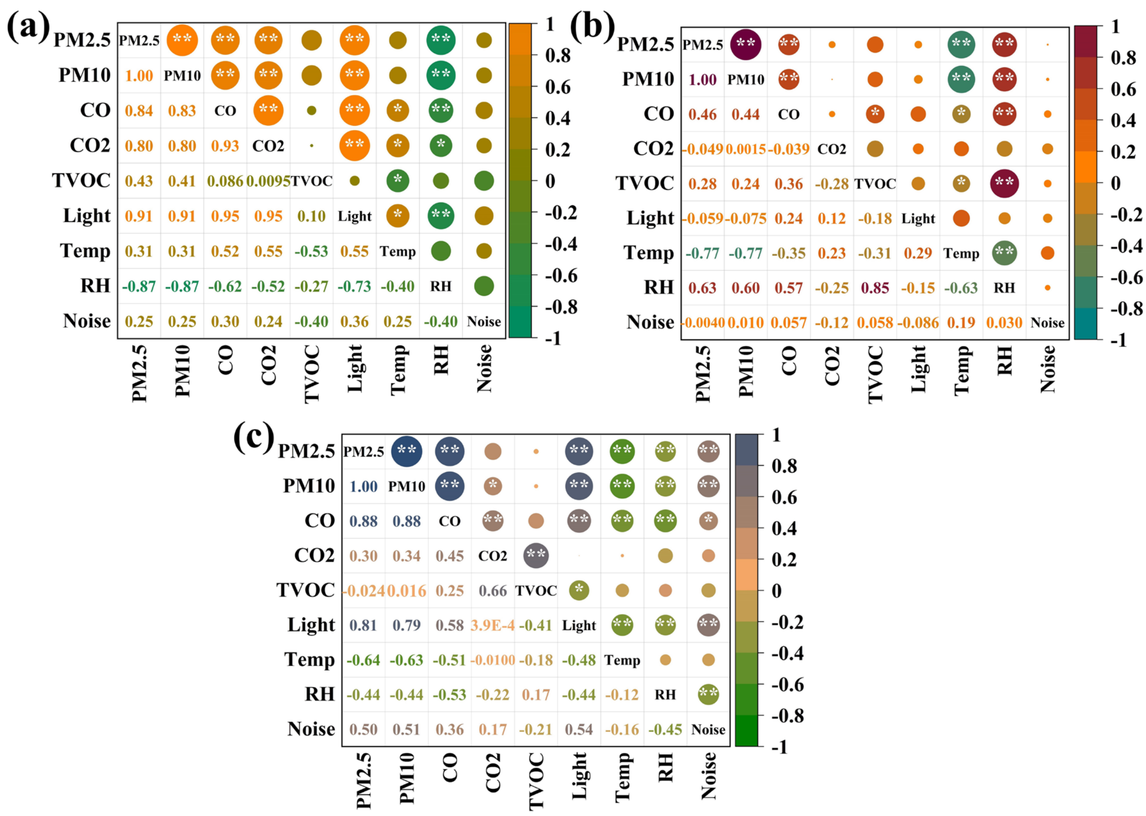

Fig. 4. Pearson's correlation plot (*p<=0.05, **p<=0.01, two-tailed test) among different parameters for (a) university, (b) school & college, and (c) primary school

Table 4. Principle Component Analysis (PCA) loadings for different parameters of different institutions

Parameters	University			School and College			Primary School		
	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
$PM_{2.5}$	0.403	-0.206	-0.070	0.449	0.276	-0.127	0.458	-0.002	-0.117
PM_{10}	0.402	-0.201	-0.078	0.440	0.299	-0.150	0.457	0.028	-0.100
CO	0.393	0.053	0.193	0.313	0.148	0.522	0.420	0.193	0.031
CO_2	0.380	0.092	0.313	-0.119	0.531	-0.013	0.166	0.556	0.342
TVOC	0.071	-0.712	-0.038	0.315	-0.453	0.246	-0.001	0.700	-0.032
Light	0.415	0.045	0.094	-0.085	0.409	0.651	0.387	-0.310	-0.083
Temp	0.225	0.490	0.341	-0.426	-0.087	0.338	-0.281	-0.093	0.636
RH	-0.352	0.089	0.358	0.453	-0.218	0.176	-0.260	0.132	-0.597
Noise	0.158	0.387	-0.774	-0.002	-0.319	0.244	0.285	-0.199	0.299
Eigenvalue	5.606	1.844	0.888	3.8874	1.4379	1.23123	4.551	1.894	1.303
Variance (%)	62.285	20.485	9.872	43.193	15.977	13.680	50.567	21.039	14.473
Cumulative Variance (%)	62.285	82.771	92.643	43.193	59.170	72.850	50.567	71.606	86.079

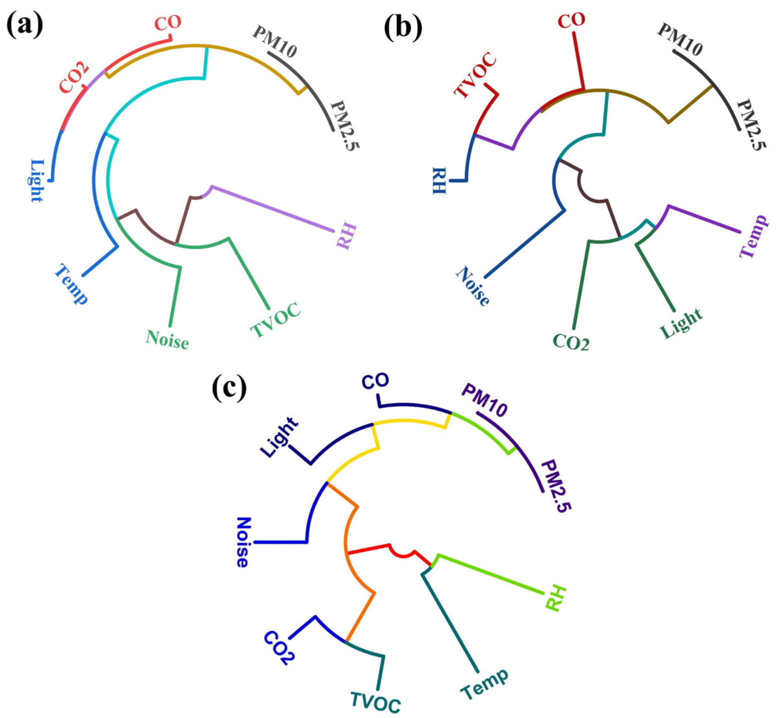

Fig. 5. Dendrogram of hierarchical cluster analysis (Average linkage method) of different parameters for (a) university, (b) school & college, and (c) primary school classrooms

Air pollutants health risk assessment

Health risk assessments for students and teachers related to air pollutants are summarized in Table 5. HQ values followed the order of $PM_{2.5}$>PM_{10} >TVOC>CO_2>CO in all cases. HQ values for $PM_{2.5}$ and PM_{10} were found to be greater than 1.0, indicating a potential for adverse health effects (i.e., posing a non-cancer health risk) to students and teachers exposed to these pollutants. Previous studies have shown that short- and long-term exposure to $PM_{2.5}$ and PM_{10} can lead to numerous health effects, including cardiovascular disorders, lung inflammation, nose, eye, throat, and skin irritation, nausea, headaches, coughing, wheezing, and respiratory diseases [58, 59].

In this study, HQ values were higher in primary schools, supported by a study, that reported indoor HQ values greater than 1.0 for both PM_{10} and $PM_{2.5}$ for students aged 7–12 [24]. Another study on school-going children in Kenya found a positive association between indoor PM levels and increased respiratory diseases in children [60]. It has also been reported that children, compared to adults, are more susceptible to the adverse effects of air pollutants due to their smaller lung capacities, higher breathing rates, and immature immune systems [61].

Teacher exposure risk in all institutions was higher than that for students due to the longer duration spent (ED) in the classrooms (Table 5). Prolonged exposure to air pollutants can lead to respiratory issues (asthma, bronchitis, and lung cancer), cognitive impairments, dementia, heart disease, stroke, and other cardiovascular issues for teachers [9, 10]. Additionally, HI values greater than 1.0 in all cases indicate that the combined exposure to multiple pollutants exceeds safe levels, suggesting a potential health risk to both students and teachers. Overall, this analysis highlights the urgent need for tailored strategies to address these targeted health impacts.

Table 5. HQ and HI of the air pollutants in the different classrooms

Classroom Type	Category	ED (year)	EF (days/year)	HQ					HI
				$PM_{2.5}$	PM_{10}	CO	CO_2	TVOC	
University	Student	4	140	1.64	0.83	0.06	0.31	0.57	3.41
	Teacher	30	160	1.88	0.94	0.07	0.35	0.65	3.89
School and College	Student	7	180	2.39	1.22	0.10	0.34	0.44	4.49
	Teacher	30	190	2.52	1.29	0.11	0.35	0.46	4.73
Primary School	Student	5	185	2.59	1.31	0.091	0.31	0.48	4.78
	Teacher	30	190	2.66	1.35	0.094	0.32	0.49	4.91

Evaluation of noise parameters

The variations of different noise parameters are detailed in Table 6 and depicted in Fig. 6. Among the three institutions, classrooms in the school and college exhibited higher noise values (high L_{max}, L_{10}, and L_{50} values). The L_{eq} values across all institutions exceeded standard levels, indicating that ambient sound levels surpassed ideal thresholds for conducive teaching and learning environments. Elevated L_{np} and NC values in classrooms indicate a relatively noisy environment, negatively affecting students' learning and well-being. Previous studies highlighted that high noise levels in classrooms can disrupt students' concentration, hinder communication, impede information retention, and contribute to stress and fatigue [4, 5, 62]. Also, high noise levels impact cognitive processes, such as attention and memory, as well as physiological responses, including increased heart rate, blood pressure, and stress hormone levels [13, 63]. These effects can significantly impair students' health and learning outcomes. A meta-analysis found that children exposed to high noise levels exhibited poorer reading comprehension and scored lower on tests compared to their peers in quieter classrooms [13].

The higher noise levels observed in the school and college were due to high-temperature levels (average 27.56 ºC). A study conducted in Pakistan mentioned that temperature significantly influences noise levels, as sound velocity increases with temperature [64]. Additionally, factors such as classroom arrangement, building design, and ventilation systems may contribute to the variation in noise readings among the institutions. A study observed that classrooms with open layouts allow more external noise to intrude, whereas soundproofing materials can effectively reduce noise levels [65]. The overall variation in noise levels among institutions may also be influenced by their surroundings, including nearby playgrounds and road traffic. Understanding these contextual factors is crucial for developing effective strategies to address noise-related issues in learning institutions.

Table 6. Variations of Lmin, L_{90}, L_{50}, L_{10}, and L_{max} at selected institutions classroom

Area Description	L_{min} (dB)	L_{90} (dB)	L_{50} (dB)	L_{10} (dB)	L_{max} (dB)
University	58.7	63.96	70.46	76.97	82.6
School and College	63.5	69.20	77.58	85.95	90.2
Primary School	69.13	71.65	77.21	82.76	85.6

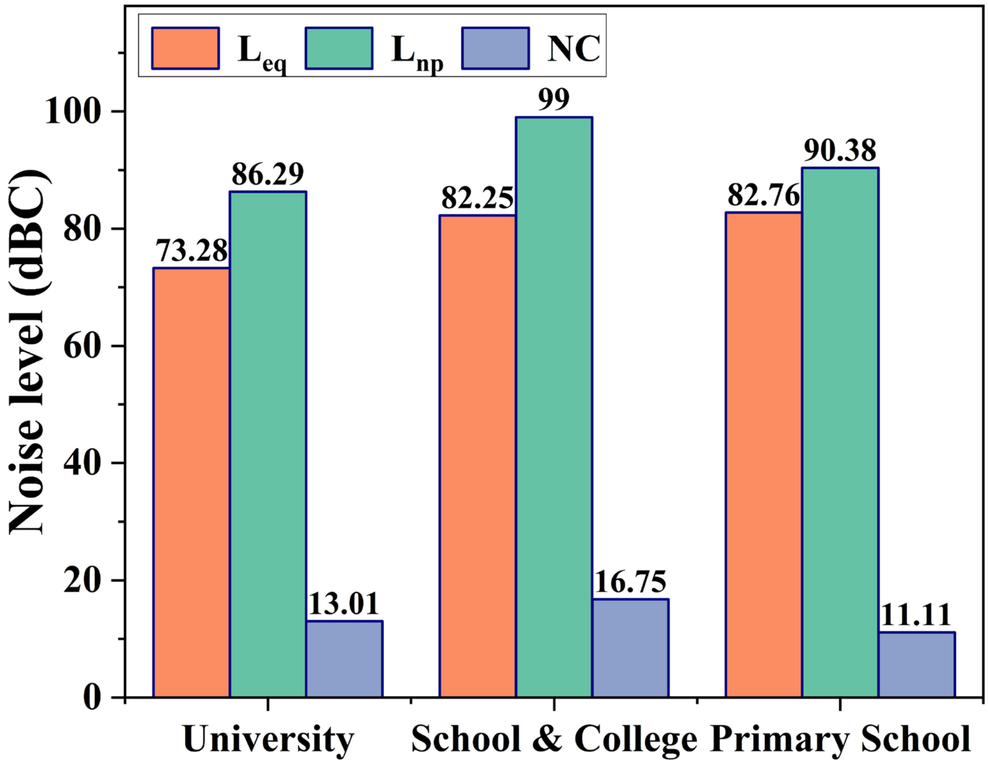

Fig. 6. Variations of L_{eq}, L_{np}, and NC in classrooms at different institutions

Conclusion

This study assessed indoor air quality parameters and noise levels in classrooms across three institutions: a university, a school and college, and a primary school. The results revealed significant variations, with mean $PM_{2.5}$ and PM_{10} levels exceeding WHO standards. Both short- and long-term exposure to elevated $PM_{2.5}$ and PM_{10} can lead to serious health issues for students and teachers, including cardiovascular disorders, lung inflammation, skin irritation, and respiratory diseases. While CO and CO_2 levels remained within the corresponding WHO and ASHRAE standard limits, noise levels surpassed WHO recommendations, creating a noisy environment that can hinder student concentration and academic performance. Given that $PM_{2.5}$ and PM_{10} levels fall within the unhealthy to moderate health categories and Hazard Quotient (HQ) values for these particulates exceed 1.0, it is crucial to install whiteboards or digital boards (especially in the primary school), effective ventilation systems, and air purifiers (such as HEPA filters) in all institutions to mitigate health risks.

To address the observed low light levels, classrooms should be equipped with improved natural light solutions (e.g., larger windows) and adjustable LED lighting to meet recommended illumination standards. Additionally, the high noise levels in all classrooms suggest an urgent need for effective soundproofing upgrades using acoustic panels, ceiling tiles, and carpets to foster a more conducive learning environment. The significant positive correlations found between $PM_{2.5}$, PM_{10}, and CO indicate that these pollutants are likely influenced by common sources within the classroom. Therefore, implementing a comprehensive IAQ management plan—which includes regular monitoring of the pollutants, maintenance of ventilation systems, and awareness training for teachers and students on the importance of indoor air quality—is essential for creating a better and healthier classroom for all.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contributions

The study was conducted by Md. Bashirul Islam and Md. Mehedi Hassan Masum under the guideline of Dr. Asiful Hoque.

Md. Bashirul Islam: Conceptualization, Methodology, Resources, Investigation, Data curation, Formal analysis, Software, Writing – original draft. Md. Mehedi Hassan Masum: Conceptualization, Methodology, Formal analysis, Visualization, Writing – review and editing. Asiful Hoque: Conceptualization, Resources, Writing – review and editing.

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Ethical considerations

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/ or falsification, double publication and/ or submission, redundancy, etc.) have been completely observed by the authors.

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